

# Supernovae and Cosmology with Future European Facilities

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Prospects for future supernova surveys are discussed, focusing on the ESA Euclid mission and the European Extremely Large Telescope (E-ELT), both expected to be in operation around the turn of the decade. Euclid is a 1.2m space survey telescope that will operate at visible and near-infrared wavelengths, and has the potential to find and obtain multi-band lightcurves for thousands of distant supernovae. The E-ELT is a planned general-purpose ground-based 40m-class optical-IR telescope with adaptive optics built in, which will be capable of obtaining spectra of Type Ia supernovae to redshifts of at least four. The contribution to supernova cosmology with these facilities will be discussed in the context of other future supernova programs such as those proposed for DES, JWST, LSST and WFIRST.

## 1. Introduction

The discovery of the accelerating expansion of the Universe [Riess et al (1998), Perlmutter et al (1999)] was one of the biggest breakthroughs of the last twenty years and was awarded the 2011 Nobel Prize for Physics. However the fundamental question remains: what drives this acceleration? One possibility is that it is driven by a mysterious component of the Universe, termed “Dark Energy” that exerts negative pressure and that constitutes about 70% of the energy density of the universe. Focus has now turned to measuring the equation-of-state parameter,  $w$  (= pressure/density) of this Dark Energy. Current measurements of  $w$  are consistent with  $-1$ , the value expected if the behaviour of Dark Energy can be described by the cosmological constant ( $\Lambda$ ) in Einstein’s field equations. Although this would perhaps be the simplest explanation, large problems remain, for example there is no natural explanation for such a small and yet non-zero value for the vacuum energy density. Other explanations such as “quintessence” and modified gravity have been proposed, and distinguishing between these models is one of the major challenges of modern physics. A measurement of  $w$  not equal to  $-1$  (at any redshift) would rule out the cosmological constant explanation and would have profound consequences for physics. Therefore there

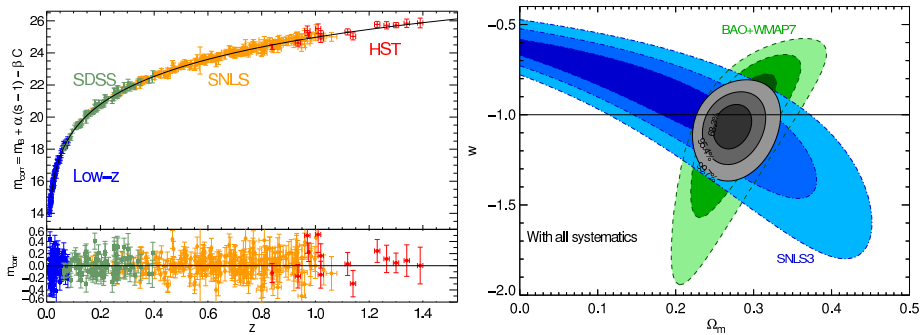


Figure 1. SNLS 3-year results [Conley et al. (2011), Sullivan et al (2011), Guy et al (2011)] Left: (reproduced from [Conley et al. (2011)]) Hubble diagram for 472 SNe Ia (123 low-z, 93 SDSS, 242 SNLS, 14 HST). Right: (reproduced from [Sullivan et al (2011)]) cosmological constraints from SNe Ia (blue), including systematics and assuming a flat universe. The grey contours show combined constraints with WMAP7 and SDSS LRG power spectra constraints (green) and a prior on the Hubble constant  $H_0$  from SHOES. (Online version in colour)

is considerable effort being directed towards improving measurements of  $w$  using several techniques including weak lensing, Baryon Acoustic Oscillations (BAO), and Type Ia Supernovae (SNe Ia).

The best constraints on Dark Energy to date measure  $w$  consistent with  $-1$  at the  $\sim 7\%$  level (including statistical and systematic uncertainties), assuming a flat universe and a constant equation of state [Sullivan et al (2011), Suzuki et al (2012)], see Fig 1. Presently systematic errors are estimated to be comparable to the statistical uncertainties in SN cosmology. The major sources of systematic error are related to photometric calibration, particularly when comparing distant SNe to nearby SN samples that have been compiled in a different way and with different rest-frame wavelength coverage. New nearby searches are addressing this problem (for examples, see papers by B. Schmidt and J. Tonry at this meeting).

A second source of systematic error arises from our lack of understanding of the colours of SNe Ia. SNe Ia show a range of colours, and the colour correlates inversely with brightness. Such a relation could be caused by dust extinction in the SN host galaxies or could be an intrinsic property of SNe Ia themselves, or a combination of the two. To make progress, any future SN survey should measure SNe Ia in multiple bands, particularly towards redder wavelengths where the effects of dust are reduced and there is evidence for reduced intrinsic dispersion [Freedman et al (2009)].

Finally, another potential systematic effect is evolution of the SN Ia population. We know that SN Ia spectra are similar at low and high redshift (up to  $z \sim 0.9$ ) [Bronder et al. (2008), Walker et al (2011)] although differences in the UV have recently been seen [Maguire et al (2012)]. We also know that SN Ia rates and broadband SNe Ia lightcurve properties are dependent on the host galaxy type. The luminosity of SNe Ia depends on host galaxy type even after correction using the usual stretch and colour correction method [Sullivan et al (2010)]. Extending the redshift range over which SNe Ia are measured will allow better control of these effects. To date only a handful of

SNe Ia have been observed at  $z > 1$  at any wavelength. Such observations are extremely difficult from the ground because (a) the SNe are faint, and (b) the peak of the SNe Ia spectral energy distribution moves into the NIR where the sky background is higher. HST has therefore been the primary route for finding such SNe [Riess et al (2007), Amanullah et al. (2010), Suzuki et al (2012)].

## 2. Future facilities

In the following sections, several upcoming projects are described that will make dramatic advances in SN Ia cosmology. These approach the problem in two main ways. The first is improving statistics (which can also lead to improved control of systematics through construction of sub-samples). The second is extending the wavelength coverage of high-redshift SN samples into the near-infrared (near-IR).

### (a) DES and VISTA

The Dark Energy Survey (DES)<sup>1</sup> is an international private-public partnership involving institutions from USA, Spain, UK, Brazil and Germany with the goal of mounting and operating a 3 sq deg CCD camera on the CTIO Blanco 4m telescope. DES will carry out a 5000 sq deg survey over 5 years starting in late 2012. It will survey the sky in g,r,i,z,Y bands.

The SN component of DES has been described in detail by [Bernstein et al. (2012)]. 30 square degrees will be imaged repeatedly in the g,r,i,z bands and is expected to result in 4000 well measured SNe Ia in the redshift range  $0.05 < z < 1.2$ . An external spectroscopy program is being planned that will provide robust redshifts of the host galaxies (which aid SN photometric classification and are necessary for accurate fitting of cosmological parameters). In addition, spectra will be obtained for a subset of the SNe themselves ( $< 20\%$ ), some of which will have detailed multi-epoch spectroscopy.

The 4m VISTA telescope, equipped with a 67 Mpix NIR camera and operated by ESO, has been carrying out public NIR surveys in Z,Y,J,H,Ks bands since 2009. The SN component within the VIDEO survey [Jarvis et al (2012)] is expected to produce about 100 SNe Ia with  $z < 0.5$  observed in Y and J bands. These SNe will overlap with the DES sample and will therefore have both optical and near-IR lightcurves.

### (b) LSST

The Large Synoptic Survey Telescope (LSST)<sup>2</sup> is a U.S.-based public-private partnership that aims to construct and operate a 8.4m survey telescope (6.7m effective diameter) equipped with a very wide field camera (9.6 sq deg) with u,g,r,i,z,y filters. The main survey will cover  $\sim 20000\text{deg}^2$  every 3-4 days, and by the end of the survey each field will have been imaged over 1000 times. The “Deep Drilling Fields” will cover a smaller area but reaching a deeper limiting magnitude per visit and with faster cadence (to be determined), thereby producing SN lightcurves of higher quality and reaching higher redshift than the main survey.

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<sup>1</sup> <http://www.darkenergysurvey.org>

<sup>2</sup> <http://www.lsst.org>

20-40 such fields are envisioned, of which the locations of 4 have already been selected. LSST is due to start operation at the end of the decade and will have a  $\sim 10$  year survey lifetime.

The SNe Ia case has been described in detail in the LSST Science book (Chapter 11, Wood-Vasey et al). For SN Ia cosmology the key gain is massive statistics: 50000 SNe Ia per year are expected, with redshift up to  $\sim 0.8$  (main survey) and up to  $\sim 1$  (Deep Drilling Fields). Such statistics also improve systematics by allowing the sample to be split into subsets, for example depending on host galaxy type. However because of the very large sample size, only a small fraction will have spectroscopic redshifts and classifications. The LSST SN survey will also allow tests on isotropy and homogeneity, and tests of SN Ia evolution. LSST will also find core-collapse SNe and measure SN rates (for all Types).

### (c) *JWST*

The James Webb Space Telescope (JWST)<sup>3</sup> is a joint project between NASA, the European Space Agency and the Canadian Space Agency. It consists of a 6.5m space observatory with four instruments optimised to the infrared wavelength range. Launch is currently expected in 2018. Being an observatory as opposed to a survey instrument, JWST's science use will be determined mainly from PI programs. JWST's key advantage for SN cosmology is sensitivity at infrared wavelengths, allowing it to reach well above  $z = 1$ . Several possible ways that JWST could advance SN cosmology have been suggested.

$z > 1$  : In the white paper "James Webb Space Telescope Studies of Dark Energy" [Gardner et al. (2010)] it is demonstrated that in 1 year using 1080 hours, JWST could find and follow 60  $z > 1$  SNe, including obtaining spectra with JWST itself.

$z > 2$ : Riess & Livio (2006) make the case in that observing at  $z > 2$ , where the effects of Dark Energy are expected to be very modest, will provide a key test for evolution in the SN Ia population. They estimate that  $\sim 1.5$  SNe Ia could be found within each NIRCAM field reaching 10nJy in K. They suggest monitoring a few NIRCAM fields with cadence  $\sim 100$  days.

$z \sim 4$ : The JWST exposure time calculator predicts that JWST can reach 2 magnitudes below peak brightness of a typical SN Ia lightcurve at  $z = 4$  in 10 000s. By monitoring 10 NIRCAM fields for 5 years, a sample of  $\sim 50$  objects could be found. Spectroscopic confirmation could be obtained using future ground-based extremely large telescopes (see next section).

### (d) *The European ELT*

Three extremely large telescope projects are currently underway: the Giant Magellan Telescope (GMT)<sup>4</sup>, the Thirty Meter Telescope (TMT)<sup>5</sup> and the European Extremely Large Telescope (E-ELT)<sup>6</sup>. These projects are at a comparable stage of development and all aim for first light around the turn of

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<sup>3</sup> <http://www.jwst.nasa.gov/>

<sup>4</sup> <http://www.gmto.org/>

<sup>5</sup> <http://tmt.org/>

<sup>6</sup> <http://www.eso.org/sci/facilities/eelt/>

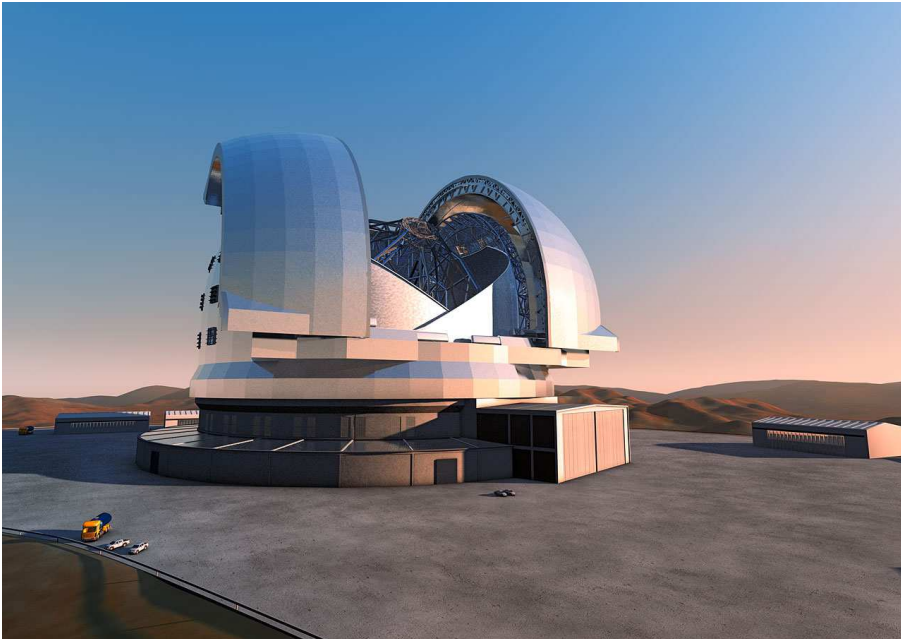


Figure 2. Artist's impression of the European Extremely Large Telescope (E-ELT). Image credit: ESO (Online version in colour)

the decade. In this paper I focus on the European ELT, but the broad conclusions are similar, or scalable, to all three projects.

The E-ELT project aims to design and construct a 39m diameter optical-IR telescope, which will be the largest optical/IR telescope in the World. The project is run by ESO on behalf of its member states. The design is a novel 5 mirror concept with adaptive optics built in, and the telescope will be situated on Cerro Armazones in Chile. The first three instruments have been selected: a diffraction-limited camera and an integral-field spectrograph for first light, and a mid-IR imager-spectrograph to arrive shortly afterwards. The full instrumentation suite will be built up over first decade of operation. Since the time of this Royal Society Discussion meeting, the ESO Council has approved the E-ELT programme subject to confirmation of funding from some member states.

The E-ELT is a general-purpose observatory and the science case is very general [Hook (ed) 2005]. In addition to its clear power for identification of varying sources from other facilities (e.g. GRBs), examples of time domain science with E-ELT include Solar System observations (including study of weather and volcanic activity), Exo-planets (including radial velocity, direct detection and transit measurements) and study of the motions of stars and stellar flares in the vicinity of the Galactic centre. Furthermore, with specialised high-time resolution detectors, E-ELT could study extreme physics (pulsars, neutron stars, black holes) stellar phenomena, transits and occultations [Shearer et al (2010)].

The E-ELT will be particularly powerful for spectroscopic observations of SNe Ia at high redshift. Because they are point sources, SN observations benefit from the telescope's adaptive optics capability. Such spectroscopic observations

are needed in order to unambiguously classify the SNe and to determine their redshifts. Simulations show that with the HARMONI integral-field spectrograph [Thatte et al (2010)] and using the telescope's adaptive optics system, the SiII feature near a rest-frame wavelength of  $4000\text{\AA}$  is clearly detected even at  $z = 4$  (at which redshift the feature is observed in the K-band; Hook, 2010). Since the presence of SiII and absence of hydrogen is the defining signature of SNe Ia, this means that it will be possible to confirm SN Types even out to  $z = 4$ . To obtain E-ELT spectroscopy of a sample of 50 objects  $1 < z < 4$  (which could be reasonably discovered by JWST, see section c) would require of order 400 hours spread over the over 5 years of the survey.

### (e) *Euclid*

Euclid is a 1.2m optical-IR space telescope within ESA's Cosmic Vision 2015-2025 programme [Laureijs et al (2011)]. Its primary science goal is precision measurement of cosmological parameters via weak lensing and galaxy clustering techniques. ESA's downselection process in October 2011 resulted in selection of Euclid for the second M-class launch slot. In June 2012 the mission passed the important milestone of adoption of the mission by ESA. Launch is currently scheduled to take place in Q4 2019.

The instrumentation consists of an optical imager and a near infrared imager and spectrograph, both with field of view of 0.5 sq deg. The satellite will be launched by a Soyuz rocket and will operate at the L2 Lagrange point for a 6 year mission duration.

Euclid's Wide survey will cover  $\geq 15000$  sq deg, with imaging in a single broad optical band (R+I+Z) to a depth of AB=24.5 ( $10\sigma$  for a point source), imaging in three near infrared bands (Y, J, H) to a depth of AB=24 ( $5\sigma$ , extended source) and NIR slitless spectroscopy to a depth of  $3 \times 10^{-16} \text{cm}^{-2} \text{s}^{-1}$  ( $3.5\sigma$  unresolved line flux).

Additional Deep fields will cover  $\geq 40$  sq deg, reaching 2 magnitudes deeper than the Wide survey in both optical and NIR imaging and NIR Spectroscopy. The Deep fields are primarily for calibration purposes but the  $\sim 40$  repeat visits will enable a vast range of additional science including detection and study of variable, moving and transient objects.

In addition, ideas for specialised dedicated surveys for SNe and microlensing of exoplanets are being considered, although these are not currently in the baseline. These will be further explored as the survey design is optimised.

For SNe Ia cosmology, one example strategy has been developed that would allow exploration of a new redshift range, to  $z \sim 1.5$ . Simulations show that 6 months of Euclid survey time could be used to carry out a survey of 20 sq deg with 4 day cadence. When combined with simultaneous ground-based observations in I and z bands, this results in 1700 well measured SNe Ia in the redshift range  $0.75 < z < 1.5$  with measurements covering a consistent rest-frame wavelength range. Such a survey would make a significant improvement in the measurement of cosmological parameters from existing surveys at the time, and would add an independent method to Euclid's primary cosmological probes, thereby enhancing the mission's overall impact.

(f) *WFIRST*

The proposed NASA mission WFIRST (Wide-Field Infra-Red Survey Telescope) emerged as the top priority large space mission in the U.S. “New Worlds New Horizons” 2010 Decadal Survey. Its science drivers are measurement of the expansion history of the Universe and galaxy clustering (exploring Dark Energy and modified gravity theories via the weak lensing, supernova and BAO techniques); Exoplanets (via microlensing); Deep NIR surveys; a Galactic plane survey; High- $z$  QSOs and a guest observer program.

Definition of the hardware is in progress. The interim report of the Science Definition Team study [Green et al. (2011)] described a 1.3m off-axis telescope operating from  $0.6 - 2.0\mu\text{m}$ , and a  $\sim 0.3$  sq deg FOV covered by imaging in 5 filters and slitless spectroscopy with  $R \sim 200$  from  $1.1 - 2.0\mu\text{m}$ . An additional  $R \sim 75$  prism would be available for SN spectroscopy. Launch is anticipated for  $\sim 2020$ , assuming phase A starts in 2013.

The WFIRST SN Ia program goals are stated as  $> 100$  SNe per  $\Delta z = 0.1$  redshift bin in the range  $0.4 < z < 1.2$  per dedicated 6 months (spread out during the mission lifetime). The goal is to achieve an error on distance modulus of  $< 0.02$  mag per  $\Delta z = 0.1$  redshift bin. They also consider an ‘optimistic’ case where the redshift range is extended to 1.5 and systematic effects are reduced.

### 3. Conclusions

There is a spectacular suite of new facilities on the horizon that will make dramatic advances in the quantity and quality of SN samples for cosmology. Several of these facilities are already planning SN programs and have made detailed predictions of the achievable results in terms of numbers of objects and in some cases cosmological constraints (e.g. in terms of the Dark Energy Task Force Figure of Merit). Such figure of merit calculations depend critically on the assumptions made for systematic effects and priors, so comparison is not straightforward and is not attempted here. However by comparing the  $N(z)$  distributions of existing and future samples we can obtain a simple visual impression of the gains we can expect (Figure 3).

In summary, the gains likely to emerge are:

- an enormous gain in statistics (at least 2 orders of magnitude) of optical SN Ia measurements, from a combination of current nearby searches, DES and then LSST
- an enormous gain (2 orders of magnitude) in numbers of observed-frame NIR observations of distant SNe, from VISTA and then space-based surveys with Euclid (survey strategy permitting) and WFIRST, potentially allowing extension of the SN Ia Hubble diagram up to  $z \sim 1.5$ .
- better control of systematic effects, arising from (a) the ability to create sub-samples from large parent samples, and (b) from the improved wavelength coverage resulting from combined optical-NIR observations of the same SNe
- extension of the SN Ia Hubble diagram to currently unexplored redshifts above 2 and up to about 4, from JWST and ELTs

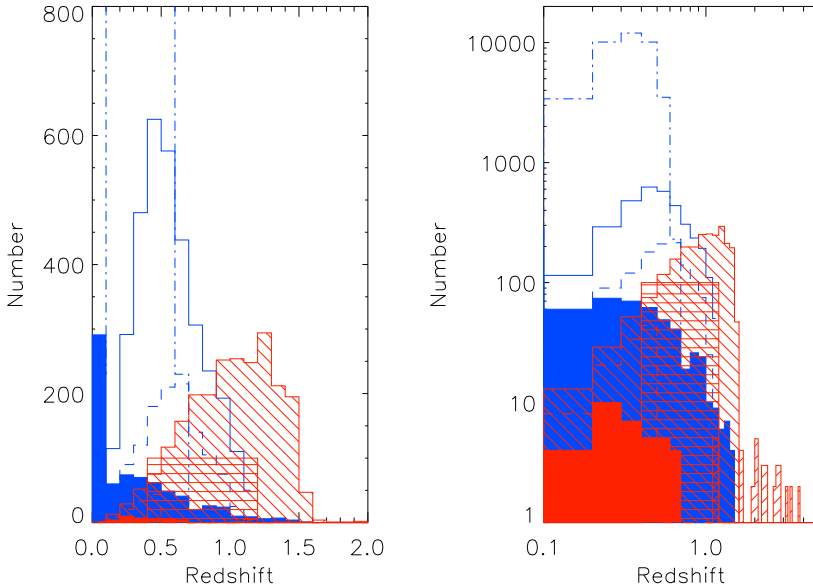


Figure 3. (Online version in colour) Redshift distributions from existing and planned SN surveys in (left panel) linear and (right panel) log space. Optical surveys are shown in blue: the existing Union 2.1 sample [Suzuki et al (2012)] (filled histogram); DES (solid line); LSST wide survey and Deep Drilling fields (dot-dashed and dashed lines respectively). Note that the LSST values are for only one year of operation and may be a factor  $\sim 10$  higher for the final sample. Near-IR samples are shown in red: the existing CSP sample [Freedman et al (2009)] (filled histogram); VISTA sample (assumed to be 100 objects sampled from the DES distribution up to  $z=0.5$ , dashed line); a possible Euclid survey if scheduling allows (hatched histogram); the WFIRST SN goals (horizontal hatched histogram); an example very high-redshift sample that could be compiled by JWST and ELTs (diagonal hatched histogram at  $z > 1$ ).



In summary the prospects are very exciting. However coordination of survey execution between facilities is required to maximise the gains; for example survey fields must be chosen so that they are observable by both space and ground-based facilities, and scheduling must permit such coordination. In particular exploitation of the synergies between JWST and the ELTs and between Euclid/WFIRST and LSST would be particularly valuable.

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